

High Input Voltage, Silicon Carbide Power Processing Unit Performance Demonstration

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A silicon carbide brassboard power processing unit has been developed by the NASA Glenn Research Center in Cleveland, Ohio. The power processing unit operates from two sources: a nominal 300 Volt high voltage input bus and a nominal 28 Volt low voltage input bus. The design of the power processing unit includes four low voltage, low power auxiliary supplies, and two parallel 7.5 kilowatt (kW) discharge power supplies that are capable of providing up to 15 kilowatts of total power at 300 to 500 Volts (V) to the thruster. Additionally, the unit contains a housekeeping supply, high voltage input filter, low voltage input filter, and master control board, such that the complete brassboard unit is capable of operating a 12.5 kilowatt Hall effect thruster. The performance of the unit was characterized under both ambient and thermal vacuum test conditions, and the results demonstrate exceptional performance with full power efficiencies exceeding 97%. The unit was also tested with a 12.5kW Hall effect thruster to verify compatibility and output filter specifications. With space-qualified silicon carbide or similar high voltage, high efficiency power devices, this would provide a design solution to address the need for high power electric propulsion systems.

I. Introduction

FUTURE NASA deep space missions will demand high power capabilities in excess of what conventional propulsion technologies can provide. The Space Technology Mission Directorate (STMD) Game Changing Division's Advanced In-Space Propulsion Project has worked to develop innovative propulsion technologies that will provide the necessary power capabilities to move cargo or humans into deep space.¹⁻³ One enabling technology under development is solar electric propulsion (SEP). To demonstrate the game-changing capabilities of SEP, a team of engineers from NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) were tasked with demonstrating a high-power SEP Hall effect thruster system. A key element of the SEP Hall effect thruster system is the power processing unit (PPU), which processes electrical power from solar arrays and converts it to the voltage and power levels required for thruster operation.

In support of the SEP brassboard system, NASA Glenn Research Center (GRC) initially developed a high input voltage, breadboard discharge supply. The development efforts to design, build, and demonstrate a breadboard discharge supply selected silicon carbide (SiC) power devices based on a comprehensive trade study of power semiconductors. Technology advances in solid-state power component topologies have led to the commercial availability of SiC transistors, which enabled the development of a high power discharge supply that could accept a higher input voltage than state-of-the-art silicon transistors. Additionally, with the use of SiC power devices, the breadboard discharge supply design yielded exceptional power efficiencies in excess of 97 percent (%).⁴

Leveraging the success of the breadboard discharge supply development, the NASA GRC team set out to design, build, integrate, and test a brassboard PPU. The primary objective of the brassboard PPU development was to

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demonstrate the PPU performance in a vacuum environment while maintaining the high performance results of the breadboard discharge supply. The brassboard PPU was required to have all of the functionality required to operate a Hall effect thruster, including the auxiliary power, master control board, telemetry, and input filters.

This paper highlights the performance demonstration and characterization test results of a high voltage, high power SiC PPU. Section II of the paper provides an overview of the brassboard SiC PPU design, including the overall PPU performance goals and individual circuit design specifications. An understanding of the brassboard SiC PPU design will provide context for the test results discussed in this paper. Section III describes the test setup for ambient and thermal vacuum environments. For each test setup, the instrumentation setup and test procedures followed to collect data are explained. The performance demonstration and characterization test results are then presented in Section IV, including the overall system efficiency and thermal performance. A description of the brassboard SiC PPU and 12.5 kilowatt (kW) Hall thruster integrated demonstration is also included in Section IV. Section V addresses future work required to advance the SiC component technology to a flight-ready design. Finally, Section V contains a conclusion based on the brassboard SiC PPU performance results presented in this paper.

II. Design Overview & Specifications

The design of the brassboard SiC PPU leverages previous development efforts for a 15kW, 300 Volt (V) input breadboard discharge supply for a Hall thruster. The breadboard discharge supply yielded exceptional performance using SiC components and a high voltage bus, so the development plan for a brassboard SiC PPU design focused on iterating upon the breadboard design. Additional functionality was added to the brassboard SiC PPU design in terms of electrical design features and thermal packaging that would enable operation in a flight-like environment.¹

The design objectives for the brassboard PPU were generally defined as demonstrating the PPU performance in a vacuum environment while maintaining the electrical performance of the discharge supply and operating a Hall effect thruster. To meet these objectives, the brassboard SiC PPU consists of input power filters, a master control board, a discharge supply, an inner magnet supply, an outer magnet supply, a heater supply, and an ignitor/keeper supply. Fig.1 provides a block diagram of the brassboard SiC PPU design.

In Fig. 1, there are two sources that provide input power to the PPU. One source is a high input bus, nominally 300 V, which is representative of a high power, high voltage regulated solar array input on a spacecraft. The second is a low voltage input bus, nominally 28 V, which was selected such that the thruster cathode can keep the cathode hot during an eclipse by running the keeper supply from a standard 28 V battery-backed power bus, and then be able to resume operation immediately when the eclipse ends.¹ All power entering the PPU is then filtered, such that the discharge supply receives power from the output of the high voltage bus input filter, and the auxiliary supplies and housekeeping DC-DC converter receive power from the output of the low voltage bus input filter.

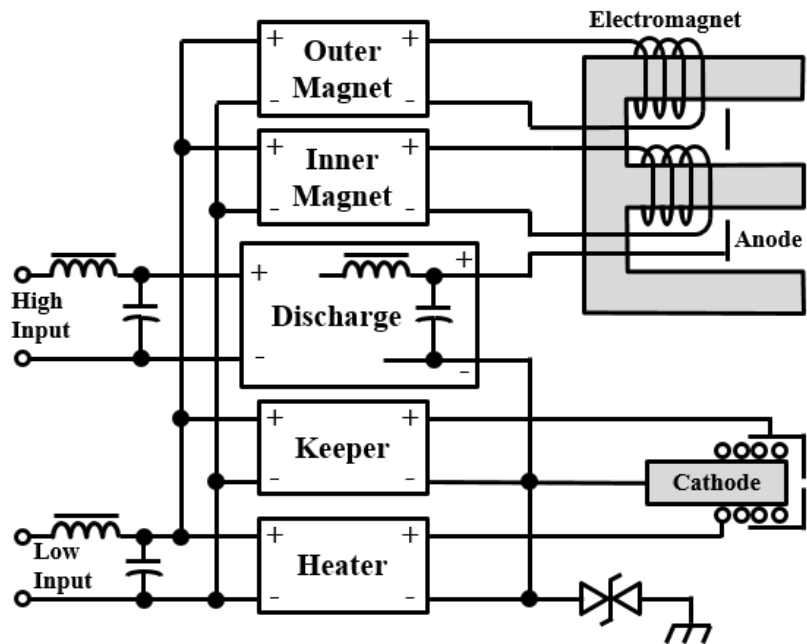


Figure 1. Hall effect thruster silicon carbide PPU block diagram.

The brassboard PPU power outputs are connected to the discharge anode and cathode, inner electromagnet, outer electromagnet, cathode heater, and cathode keeper of a Hall effect thruster. The design goals for each brassboard SiC PPU power are given by Table 1, where each brassboard SiC PPU power supply is named after the part of the thruster that it provides power to.¹

Table 1. Brassboard SiC PPU power supply output specifications.

	Maximum Output Power	Output Voltage Range	Output Current Range	Regulation Mode	Line/Load Regulation	Ripple
Discharge Supply	15 kW	300-400 VDC	37.5-50 ADC	Voltage	$\leq 2\%$	$\leq 5\%$ peak-peak of regulated parameter
Inner Magnet and Outer Magnet Supplies	200 W	2-20 VDC	1-10 ADC	Current	$\leq 2\%$	$\leq 5\%$ peak-peak of regulated parameter
Heater Supply	324 W	6-36 VDC	3-9 ADC	Current	$\leq 2\%$	$\leq 5\%$ peak-peak of regulated parameter
Keeper Supply	90 W	10-30 VDC	1-3 ADC	Current	$\leq 2\%$	$\leq 5\%$ peak-peak of regulated parameter

A. Discharge Supply

The brassboard discharge supply design is based upon the breadboard discharge supply, which has a nominal 300 V input and utilized SiC components. The breadboard design consists of two 7.5 kW discharge modules whose outputs are connected in parallel. The topology of a single discharge module is a full-bridge converter with paralleled SiC MOSFETs and a single bridge rectifier using SiC Schottky diodes. Pulse-width-modulation (PWM) based on peak and average current control was implemented to enable a fast response to voltage variations and over current fault protection within the breadboard discharge module. With the breadboard design, the efficiency, control modes, and component thermal dissipations of the discharge supply were established.⁴

Subsequent design modifications were made to further improve the performance or functionality of the discharge supply. The first design iteration was to parallel the gate drives for the paralleled SiC MOSFETs to simplify the design. A second design modification was to use current transformers to sense the current through each leg of the bridge, which enabled more accurate sensing of the MOSFET current and the ability to detect potential short circuits in a single inverter leg. Another improvement from the design iterations was to increase the switching frequency from 20 to 30 kHz. The increased switching frequency had little effect on efficiency and allowed for a smaller transformer design. With each of these design iterations for the brassboard PPU discharge supply, the general printed circuit board layout of the grounding and shielding planes were also improved.

B. Auxiliary Supply

There are four auxiliary supplies which provide power to the Hall thruster inner electromagnet, outer electromagnet, cathode heater, and cathode keeper. All of the auxiliary supplies draw power from the low voltage bus, such that they can provide power to the Hall thruster during an eclipse. The auxiliary inner electromagnet and outer electromagnet supplies are separate, which enables flexibility in terms of characterizing thruster performance with separate electromagnet controls. The design of each auxiliary supply was based on the discharge supply and is realized with a full-bridge topology. However, unlike the discharge design, the auxiliary supplies use low-voltage, silicon-based power devices. Each auxiliary supply contains a peak- and average-current-mode PWM controller to regulate the output over the range defined in Table 1. Each auxiliary supply contains a telemetry circuit that measures the output voltage and current; the measured output current serves as the current feedback for the auxiliary controller and both voltage and current telemetry measurements are sent to the PPU master control board (MCB). The MCB also receives status outputs from each auxiliary supply in order to protect against input under-voltage, input over-voltage, output under-current, and bridge over-current operation.

C. Master Control Board

The brassboard SiC PPU receives commands through a digital interface referred to as the System Control Board (SCB). The SCB then sends analog command signals to a MCB. The primary purpose of the MCB is thus to provide a communication and control interface between the power supply modules and SCB within the brassboard SiC PPU. The MCB receives both analog and digital commands and setpoints from the SCB and analog and digital telemetry

from the power supply modules and input filters. Some of the telemetry that is passed to the SCB is generated by the MCB, including over-voltage (OV) and under-voltage (UV) for the high voltage bus, the low voltage bus, and the cathode-to-ground. To synchronize the power modules, the MCB generates four synchronization signals. It also provides an interlock circuit to disable the discharge supply based on select fault conditions, generates the keeper ignitor pulse command, and implements the discharge supply voltage and current limit control loops with soft start.

D. Input Filter

Two separate discrete input filters are implemented in the brassboard SiC PPU design – one for each input power bus. The high voltage bus input filter accepts a raw input ranging from 250 to 330 V directly from the PPU connectors, provides both common and differential mode low-pass filtering with a corner frequency of approximately 7 kHz, and attenuates noise generated by the discharge supply and thruster. The filter conditions and distributes current magnitudes in excess of 50 Amperes (A) while yielding a minimal impact to the overall PPU efficiency. In addition to filtering the high voltage bus, it also contains telemetry circuitry to sense the high voltage bus input voltage and current. Similar in design to the high voltage bus input filter, the low voltage bus input filter accepts a raw input ranging from 23 to 36 V directly from the PPU connectors, provides both common and differential mode low-pass filtering at a corner frequency of about 7 kHz, and attenuates conducted emissions from the auxiliary supplies and thruster. The low voltage filter design also includes telemetry circuitry to measure low voltage bus input voltage and current and a commercial off-the-shelf DC-DC converter to provide housekeeping power.

III. Test Setup

The 15kW brassboard SiC PPU, in Fig. 2, was tested under ambient and thermal vacuum conditions in order to demonstrate the electrical and thermal performance of the design.

During ambient testing, performance data was collected to characterize the overall PPU efficiency, input voltage ripple, input current ripple, output voltage ripple, and output current ripple per the design specification in Table 1. The ambient test setup, given by Fig. 3, shows the main components of the test setup. Two separate laboratory power supplies were used to provide power to the PPU; the high-voltage power supply was nominally 300 V and the low-voltage power supply was nominally 28 V. At the output of each PPU power supply, custom-built resistive load banks were used to simulate different power level load conditions. Within approximately one foot of the input and output power connectors to the PPU, calibrated digital voltage meters and calibrated current shunts were placed to measure voltages and currents.

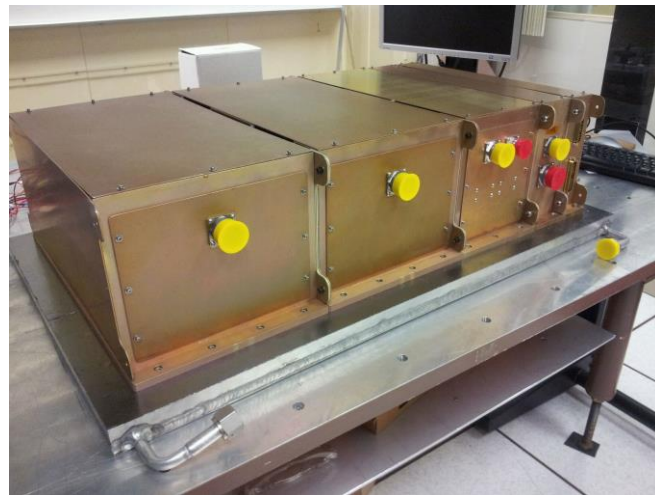


Figure 2. 15 kW brassboard SiC PPU hardware.

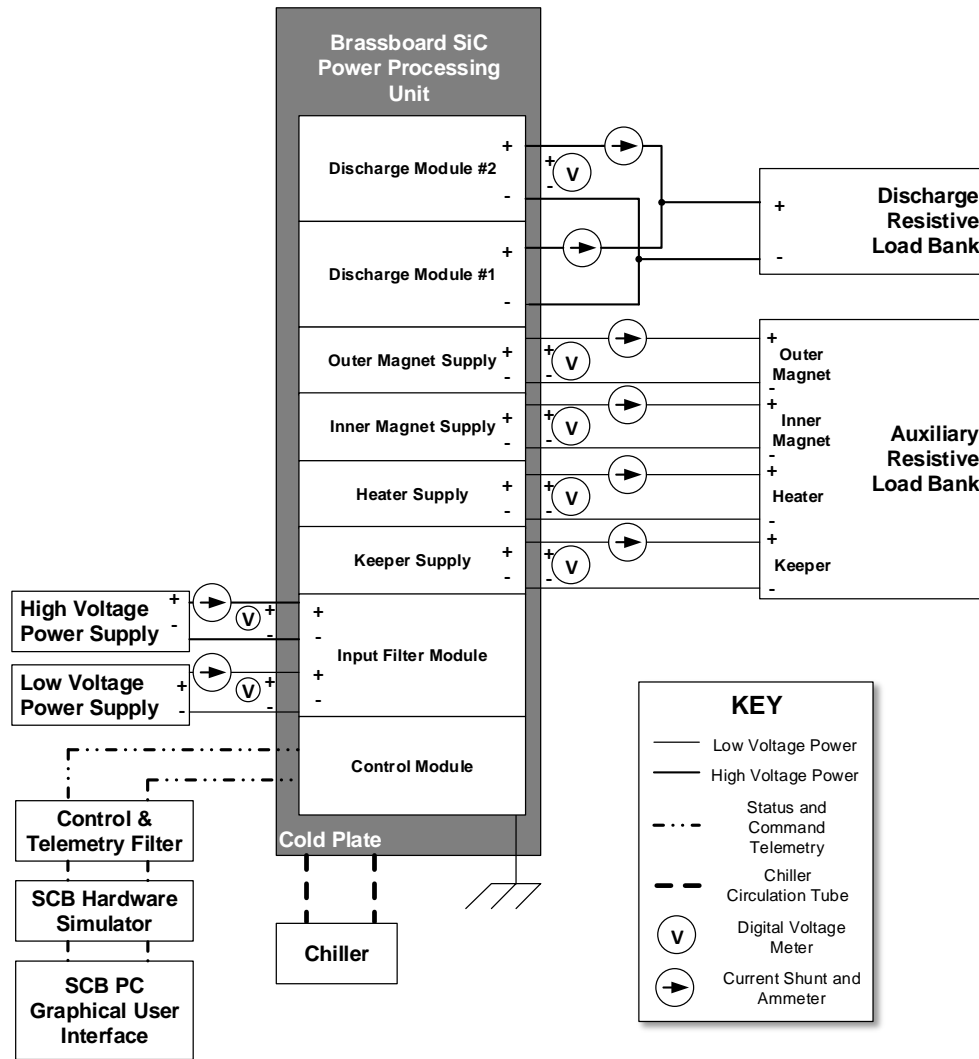


Figure 3. Brassboard SiC PPU ambient test setup diagram.

Because the final brassboard SCB development is still on-going, it was not possible to integrate the SCB hardware with the brassboard SiC PPU for characterization testing. In order to represent the basic functions of the SCB, an SCB simulator and computer with a graphical user interface (GUI) were used. PPU control and telemetry signals were filtered external to the PPU prior to interfacing with the SCB simulator. With the SCB simulator, test operators could monitor telemetry and flag statuses, adjust power supply set points, and enable or disable individual supplies. The SCB simulator also enabled test operators to automatically store test data while running the PPU for future analyses.

A chiller with a water-cooled cold plate were used to maintain the PPU baseplate temperature at a fixed value during ambient testing. A calibrated oscilloscope and probes enabled the measurement of voltage and current ripple at the same location as the voltage and current sense leads. Additionally, a data acquisition system and thermocouples monitored critical component temperatures within the PPU during testing. For each test condition, measurements were taken when the PPU had reached thermal steady-state, or when the individual component temperatures were increasing at a rate less than or equal to 0.1 degree Celcius ($^{\circ}\text{C}$) per minute.

The vacuum test was primarily conducted to demonstrate PPU performance in a relevant space-like environment. The data collected during the vacuum test was qualitatively used to demonstrate that the vacuum environment did not impact the PPU's electrical performance as compared to an ambient test environment. The PPU was placed inside a vacuum facility at NASA Glenn, with all power and control signals passing through vacuum-rated feed

through connectors. Since the goal of the vacuum test was to demonstrate that the brassboard SiC PPU was capable of operating in vacuum, voltage and current data were only recorded from the SCB simulator GUI telemetry. An analysis of previous ambient test data revealed that the SCB simulator GUI telemetry was within 2% of the calibrated meter measurements, which enabled the use of the GUI data as the primary measurements for the vacuum test. During the vacuum test, the brassboard SiC PPU was operated at cold plate temperatures ranging from 5 to 50 °C to demonstrate that the PPU performance was consistent across a wide baseplate temperature range.

IV. Performance Results

A. Efficiency

The 15kW brassboard SiC PPU test results demonstrated a significant improvement in overall efficiency in comparison to state-of-the-art PPU designs. As part of the ambient testing, calibrated measurements of input voltage, input current, output voltage, and output current were recorded over a wide range of test conditions. The efficiency was calculated from the calibrated meter readings as the sum of the output power from the discharge and auxiliary supplies divided by the sum of the input power from the high voltage and low voltage power supplies. The peak overall efficiencies observed were between 96 and 98% for input voltages ranging from 270 to 330 V and for output voltages ranging from 300 to 500 V, as shown in Figs. 4-7.

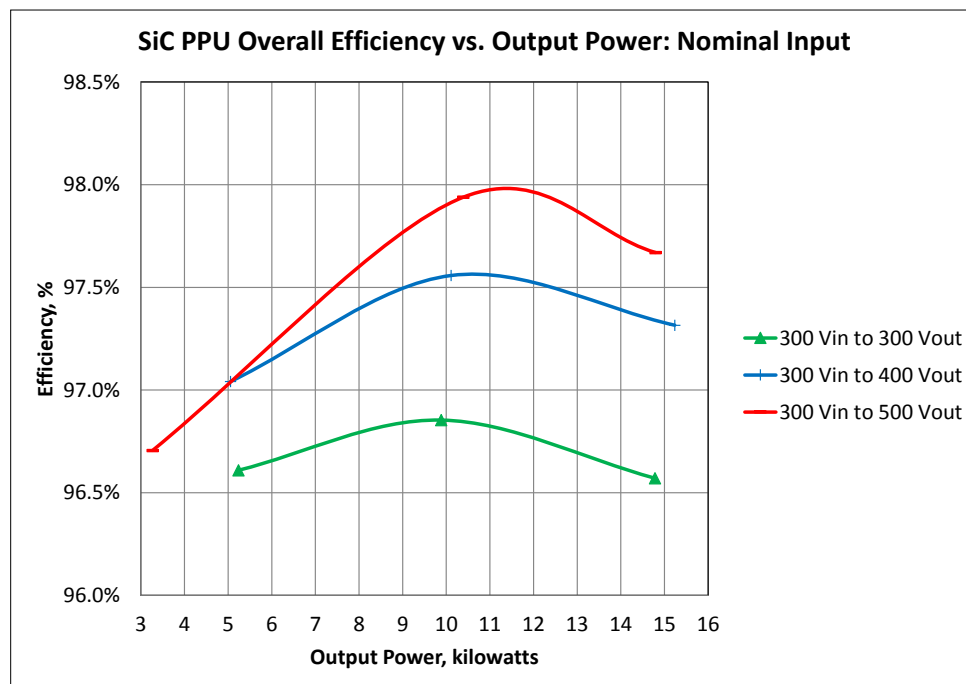


Figure 4. Brassboard SiC PPU overall efficiency vs. output power for nominal 300 V input and varying discharge supply output voltage

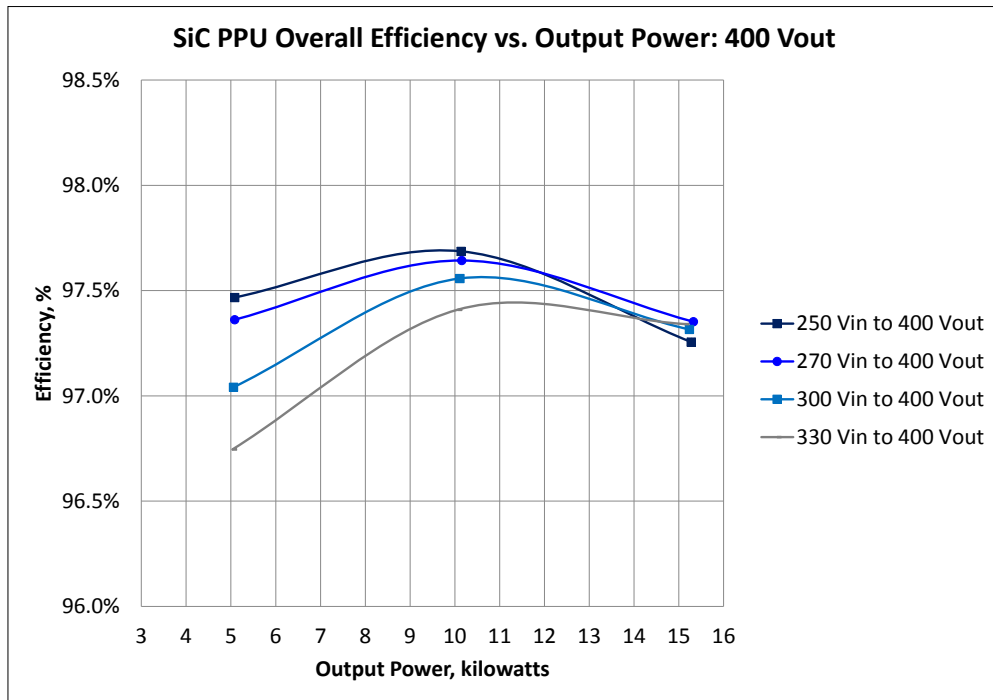


Figure 5. Brassboard SiC PPU overall efficiency vs. output power for varying input voltage and 400 V discharge supply output.

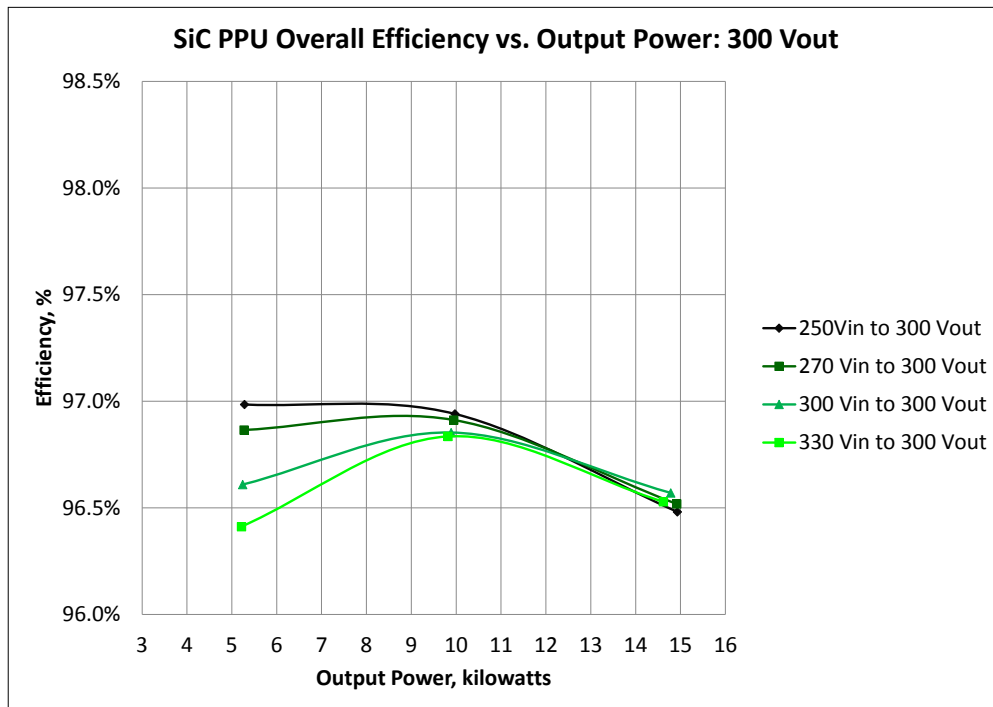


Figure 6. Brassboard SiC PPU overall efficiency vs. output power for varying input voltage and 300 V discharge supply output.

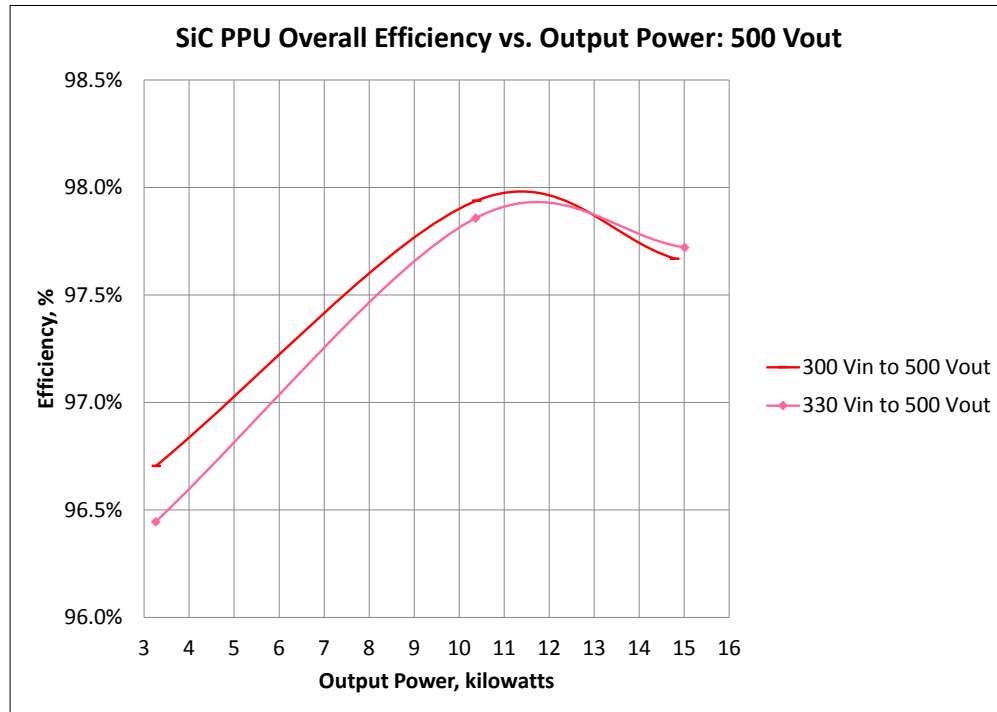


Figure 7. Brassboard SiC PPU overall efficiency vs. output power for varying input voltage and 500 V discharge supply output.

For the efficiencies plotted in Figs. 4-7, all four of the auxiliary supplies were operating with a nominal 28-Volt input power bus and with output current settings representative of a Hall effect thruster. Each plot highlights variations of the discharge voltage setting or the high voltage bus input. Fig. 4 shows efficiency curves for a constant 300 V high voltage bus input and varying discharge supply output voltages. At the highest discharge output voltage tested, or at a discharge voltage of 500 V, the highest overall SiC PPU efficiency of 97.9% was achieved at 10.3 kW of discharge output power. Figs. 5 and 6 show overall PPU efficiency plots for varying high voltage bus input voltages at the boundaries of the specified discharge supply output voltage range, or at 300 V and 400 V respectively. In these plots, the low input voltage efficiency is consistently greater than the high input voltage efficiency at low discharge power levels. At the full power SiC PPU output, or at 15 kW, the efficiencies are consistent as the input voltage changes. Fig. 7 shows results that were collected at a discharge voltage setting of 500 V, which exceeds the discharge supply output performance specified in Table 1. In order to achieve this voltage, the high voltage input needed to be greater than or equal to 300 V, hence there are only efficiency curves given for input voltages that meet this criteria.

B. Line Regulation, Load Regulation, and Output Ripple

During ambient testing, the line regulation, load regulation, and output ripple from each power supply were assessed using calibrated meter measurements and calibrated oscilloscope waveforms. For the discharge supply, voltage regulation was assessed, as voltage is the regulated parameter. For the auxiliary supplies, current regulation was assessed. Line regulation was defined as the ability of a power supply to maintain its output voltage given a variation in the input line voltage. For collecting test data to assess line regulation, the input voltage was varied across the full input range, or 250 to 330 V for the high voltage bus and 23 to 36 V for the low voltage bus. While the input voltage was varied, the output regulated parameter was held constant and the load resistance of the supply under test was set at the maximum load condition. Line regulation was then calculated as the percent change in regulated output divided by the change in input voltage. For load regulation, the input bus voltage and the output regulated parameter setting were fixed. The load resistance was then varied from approximately 30 to 100% of the full power output. The load regulation was calculated as the percent change in the regulated output divided by the nominal value of the regulated parameter. Output ripple was defined as the measured amplitude of the regulated

parameter divided by the full scale value for each supply. Table 2 shows a sampling of the line regulation, load regulation, and output ripple calculations for each power supply. The test conditions column indicates what the setting was for the regulated output parameter and the full-scale value, which was used in the calculation of output ripple.

Table 2. Brassboard SiC PPU line regulation, load regulation, and output ripple results.

	Test Conditions (full-scale value)	Line Regulation, %	Load Regulation, %	Ripple, %
Discharge Supply	V _{out} = 400 VDC (400 VDC)	2.90%	0.74%	1.25%
Inner Magnet Supply	I _{out} = 5 ADC (10 ADC)	0.08%	0.08%	0.08%
Outer Magnet Supply	I _{out} = 5 ADC (10 ADC)	0.03%	0.02%	0.20%
Heater Supply	I _{out} = 5 ADC (9 ADC)	0.08%	0.04%	0.20%
Keeper Supply	I _{out} = 2 ADC (3 ADC)	0.01%	0.02%	0.80%

Given the brassboard SiC PPU specifications and design goals in Table 1, the calculated line regulation, load regulation, and output ripple results in Table 2 demonstrate that the PPU output characteristics meet or exceed the majority of the performance objectives. Additional PPU ambient test data collected at other operating conditions was consistent with the results presented in Table 2. The only parameter that did not meet the design specification was the discharge supply line regulation. While the discharge line regulation exceeded the maximum design specification of 2% at a 15 kW, 400 V discharge output, it was accepted as sufficient and characterization testing proceeded towards demonstrating the ability of the brassboard SiC PPU to operate in ambient and vacuum environments and to operate a Hall effect thruster.

C. Thermal Results

Throughout the ambient and vacuum testing, steady-state component temperatures were recorded. An analysis was performed on the steady-state component temperatures to demonstrate that electrical performance was not impacted by the vacuum environment. For both the ambient and vacuum testing at a high input voltage of 300 V, a low input voltage of 28 V, and a discharge output of 400 V and 15 kW, the thermal results are summarized in Table 3.

Table 3. Brassboard SiC PPU thermal data summary.

Brassboard SiC PPU Thermal Result Summary					
High Voltage Input: 300 VDC					
Low Voltage Input: 28 VDC					
Discharge Output Voltage Setting: 400 VDC, Discharge Output Power: 15 kW					
Component Temperature	Ambient Steady State Temperature, C <i>Baseplate at 25 C</i>	Vacuum Steady State Temperature, C <i>Baseplate at 25 C</i>	Vacuum Steady State Temperature, C <i>Baseplate at 50 C</i>	Vacuum Steady State Temperature, C <i>Baseplate at 5 C</i>	ΔT (Vacuum-Ambient) <i>Baseplate at 25 C</i>
Discharge Module 2, Inside Transformer Windings	54.6	67.3	97.2	61.4	12.7
High Voltage Bus Input Filter Differential Inductor	47.6	66.2	81.5	51.5	18.6
Housekeeping Power Supply, DC-DC Converter	38.8	53.8	73.2	36.5	15.1
Discharge Module 2 Transformer Case	45.9	52.5	74.8	35.2	6.6
Discharge Module 2 SiC MOSFET	33.3	35.3	58.8	16.3	2.0
Low Voltage Bus Total Input Current Sensor	33.1	45.6	64.8	27.7	12.4
Discharge Module 2 Gate Drive Board	35.9	42.2	64.3	24.3	6.4
Discharge Module 2 SiC Output Rectifier Diode	38.7	40.6	64.1	21.5	1.9
Discharge Module 2 Baseplate Temperature	25.6	26.7	50.1	6.9	1.1

Table 3 shows steady-state component temperatures provided for a nominal baseplate temperature of 25 °C in both ambient and vacuum environments. The far right column indicates the calculated temperature difference between the vacuum and ambient temperature data at baseplate temperature of 25 °C. The components with the highest temperature difference are the discharge module transformer windings and the high voltage bus differential inductor. Additionally, the DC-DC converter providing housekeeping power and the low voltage bus current sensor operated at higher temperatures in the vacuum environment. All component temperatures measured during both ambient and vacuum testing were within the component temperature ratings. Also, the slightly higher temperatures measured during vacuum testing compared to ambient testing are attributed to the lack of convection cooling in the vacuum environment. Thermal data is also included in Table 3 for the same operating conditions in vacuum at elevated and reduced baseplate temperatures of 50 and 5 °C. The thermal data collected indicates that component temperatures vary linearly when operating the brassboard SiC PPU at a constant operating point and varying the baseplate temperature.

The worst-case thermal operating condition for the brassboard SiC PPU was observed at a discharge output of 300 V at 15 kW with a high voltage input of 250 V. The worst-case component temperatures were within 5 °C of the temperatures presented in Table 3, so they were not included as they were still well within the materials and component temperature operating ranges. Overall, the test results revealed that the thermal design was adequate for both ambient and vacuum PPU operation, as most of the component temperatures were within 30 °C of the baseplate temperature for both the ambient and vacuum test results.

D. Integrated Thruster Demonstration

Following the ambient and vacuum characterization testing, the brassboard SiC PPU was integrated with a 12.5 kW Hall Thruster Technology Demonstration Unit 1 (TDU-1) at the NASA Glenn Research Center in Vacuum Facility 5. The integrated thruster demonstration confirmed the ability of the brassboard SiC PPU to power the TDU-1 thruster across the PPU's input and output operating ranges. Additionally, test results confirmed that the brassboard SiC PPU was stable when powering a plasma load. Discharge current oscillations that were captured during the integrated test will be used to characterize the output stability and verify the performance of the discharge output filter design. Fig. 8 illustrates the test configuration for the integrated thruster demonstration. During the integrated thruster test, the Hall effect thruster was operated in a vacuum facility. Vacuum rated feedthroughs carried power between the Hall effect thruster in the vacuum chamber and the brassboard SiC PPU. The brassboard SiC PPU test setup for the integrated thruster demonstration was the same as the ambient test setup previously described in Section III. The thruster data acquisition and propellant feed system was separate from the brassboard

SiC PPU test setup. During the integrated thruster demonstration, data was collected at discharge supply power levels ranging from 3 kW to 12.5 kW and discharge voltage settings ranging from 300 to 500 V. A specific discussion of the discharge supply output filter design and integrated thruster test current oscillations are addressed in a concurrent publication.⁵

V. Forward Work

In order to take the brassboard SiC PPU to a flight design, additional work is needed in terms of developing SiC space-rated components. The SiC power devices used in the 15 kW brassboard PPU contributed to the demonstrated superior performance over state-of-the-art PPU topologies, which rely on silicon-based, space-rated power devices. Research efforts led by NASA's Goddard Space Flight Center and Glenn Research Center have investigated the ability of commercially available SiC power devices to operate in space radiation environments. To date, none of the commercially available SiC power devices under investigation have been able to pass all of the required space environment radiation tests. Specifically, initial radiation test results on commercially available SiC devices have concluded that the SiC devices show high tolerance to total ionizing dose (TID) radiation, but low tolerance to single-event effects. On-going research is being performed to better understand and analyze the failure modes of the SiC power devices that were damaged during radiation testing. Ultimately, additional technology development and investment to develop a fully radiation tolerant SiC device is required for the SiC technology to truly become a game-changing capability for future SEP missions.⁶



Figure 8. Brassboard SiC PPU integrated thruster demonstration test setup.

VI. Conclusion

The performance demonstration of a 15kW brassboard SiC PPU under both ambient and thermal vacuum conditions yielded promising results for the future of high voltage, SiC power processing designs for future NASA missions requiring SEP. Characterization test results of the brassboard SiC PPU yielded exceptional full power peak system efficiencies in excess of 97% with all component temperatures within 30 °C of the baseplate temperature in an ambient environment. Comparison of the thermal steady state test data from the ambient and vacuum tests demonstrated that the vacuum environment did not impact the PPU's electrical performance. An analysis of the data collected during ambient testing also indicated that the line regulation, load regulation and output ripple of each supply were within the specified design limits, with only slight performance deviation being the discharge line regulation. An integrated thruster test demonstrated the brassboard SiC PPU's compatibility with a technology demonstration unit thruster. To realize the exceptional performance benefits of a high input voltage SiC PPU in future SEP missions, future work is necessary to ensure that SiC power devices are able to withstand the space radiation environment.

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